MEPAG 2012 Goal IV update

Based on incorporation of new analysis from the P-SAG

Draft for community review.

Please send comments to hamilton@boulder.swri.edu and Charles.J.Budney@jpl.nasa.gov.

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GOAL IV: PREPARE FOR HUMAN EXPLORATION

Introduction

Goal IV refers to the use of robotic flight missions (to Mars) to prepare for the first potential human missions (or set of missions) to Mars. Robotic missions serve as logical precursors to eventual human exploration of space. In the same way that the Lunar Orbiters, Ranger and Surveyor landers paved the way for the Apollo Moon landings, a series of robotic Mars Exploration Program missions is charting the course for potential future robotic-assisted human exploration of Mars.

It is obvious that preparing for the human exploration of Mars would involve precursor activities in several venues, including on Earth (e.g., in laboratories, in computers, and in field analogs), in low Earth orbit (including the International Space Station), and probably on nearby celestial objects such as the Moon and asteroids. Although all are important, the scope of this document is limited to precursor activity related to the Mars flight program. Connectivity between all of these precursor activities needs to be maintained separately.

Also recommended to be maintained separately is a technology demonstration roadmap which may utilize the above venues, as well as Mars itself, to prove critical technologies in a "flight-like" environment. Demonstrating technologies necessary to conduct a human mission to Mars is a necessary part of the forward path and could be considered complementary to the required science data cited in this document.

History of Goal IV Revisions

A major attempt at revising Goal IV was completed in 2005 (following the 2004 National Vision for Space Exploration and subsequent planning activities). The revision effort included the formation of two parallel MEPAG study teams, Beaty et al., 2005 and Hinners et al., 2005. Each prepared reports that became the foundations for Goal IV Objective A (a prioritized listing of the investigations and measurements necessary to safely and effectively carry out the first human mission to Mars), and Goal IV Objective B (a roadmap that demonstrated the technologies on the critical path to the first human mission), respectively. Established more recently, Objective C (critical atmospheric measurements that would reduce mission risk and enhance overall science return) was derived from an objective that was originally part of Goal II.

The 2010 revision of Goal IV is based on analysis conducted over a period of about four months between 2009-2010 by Lim et al. (2010). It considered both (1) new scientific and exploration data about Mars and (2) planning information related to the Design Reference Architecture (DRA) 5.0 document, released in late 2009. A considerable number of experts were consulted in the process of revising recommended investigations and priorities.

- Objective A, which is organized into a prioritized list of investigations, has been updated. This structure is parallel to that of the objectives in Goals I, II, and III.
- Former Objective B has been removed because it was inconsistent with the overall structure and purpose of the MEPAG Goals Document. Although the integrated technology roadmap within former Objective B was a crucial component in illustrating the sequence of missions, and necessary technology and infrastructure that must be

present before the first human landing, it was decided to remove this section from the latest revision. The details of the roadmap within this former objective could not be described as precisely as in flight investigations. Therefore, we recommended to establish this content in a new "sister" document maintained by MEPAG. The periodic maintenance of this document would allow it to track to specific target dates as they evolve with time and connect to specific NASA initiatives when they become available.

- Former Objective C, which relates to a set of atmospheric measurements, has been merged with Investigation IVA-1B ("Determine the atmospheric fluid variations from ground to >90 km that affect Aerocapture, Aerobraking, EDL and TAO including both ambient conditions and dust storms"). There was previously an unnecessarily high degree of overlap between the two.

The 2012 revision is based on analysis conducted by the joint MEPAG-SBAG (Small Bodies Assessment Group) Precursor Strategy Analysis Group (P-SAG 2012). The P-SAG was chartered to update what measurements are needed before the first human missions to the Martian system (as described in DRA 5.0). The P-SAG report provides additional measurement details beyond those described here.

- Note that the P-SAG measurements relevant to human missions to Phobos/Deimos are not described here. Check the SBAG website for details (http://www.lpi.usra.edu/sbag/).

References

Beaty, D.W., Snook, K., Allen, C.C., Eppler, D., Farrell, W.M., Heldmann, J., Metzger, P., Peach, L., Wagner, S.A., and Zeitlin, C., (2005). An Analysis of the Precursor Measurements of Mars Needed to Reduce the Risk of the First Human Missions to Mars. Unpublished white paper, 77 p, posted June 2005 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.jpl.nasa.gov/reports/index.html.

Drake, B.G, editor, (2009). NASA/SP-209-566, Mars Design Reference Architecture 5.0, 83p document posted July, 2009 by the Mars Architecture Steering Group at http://www.nasa.gov/pdf/373665main_NASA-SP-2009-566.pdf

Hinners, N.W., Braun, R.D., Joosten, K.B., Kohlhase, C.E., and Powell, R.W., (2005), Report of the MEPAG Mars Human Precursor Science Steering Group Technology Demonstration and Infrastructure Emplacement (TI) Sub-Group, 24 p. document posted July, 2005 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.jpl.nasa.gov/reports/index.html.

Committee on Precursor Measurements Necessary to Support Human Operations on the Surface of Mars (2002), Safe on Mars Precursor Measurements Necessary to Support Human Operations on the Martian Surface, NATIONAL ACADEMY PRESS, Washington, D.C.

P-SAG (2012) Analysis of Strategic Knowledge Gaps Associated with Potential Human Missions to the Martian System: Final report of the Precursor Strategy Analysis Group (P-SAG), D.W. Beaty and M.H. Carr (co-chairs) + 25 co-authors, sponsored by MEPAG/SBAG, 72 pp., posted July 2012, by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.jpl.nasa.gov/reports/.

Timing and Priorities

The P-SAG (2012) was asked to consider preparation for all potential human missions to the martian system. This included not only human missions to the martian surface, but also human missions to Mars orbit, to Phobos and/or Deimos, and sustained human presence on the martian surface. Human missions to Mars orbit (or to Phobos and/or Deimos) were defined as occurring before the first human mission to the martian surface. Sustained human presence would occur after the first set of human missions to the martian surface. In addition, precursor information for determining the architecture (i.e., which set of missions and choices like whether or not to use areocapture) of the human mission to the martian surface would be needed earlier than information necessary to design the surface systems (e.g., actual hardware to be flown). To ease description of each of these objectives, a shorthand was developed as shown in Table IV-1 below:

Table IV-1 Shorthand for human mission Goals timing.

IV-	Needed to plan human missions to Mars orbit
IV Early	Needed to plan architecture of the first human missions to the martian surface
IV Late	Needed to design hardware for first human missions to the martian surface
IV+	Needed for sustained human presence on the martian surface

Priorities

Unlike Goals I-III, which focused on answering scientific questions, Goal IV addresses issues related to increasing safety, decreasing cost, and increasing the performance of the first crewed mission to Mars. Priorities among the multiple investigations in the P-SAG report were determined by first assessing the impact of revelant data within each investigation, and then assessing the value of new precursor data against the criteria listed in Table IV-2.

Table IV-2 Criteria for setting priorities used by the P-SAG.

High:	Recognized as an enabling critical need or mitigates high risk items (items can include crew or architectural performance)
Medium:	Less definitive need or mitigates moderate risk items
Low:	Need uncertain or mitigates lower risk items

Priorities for the investigations in Objective A (below) are a combination of the P-SAG priorities in Table IV-1 and timing in Table IV_2. Measurements needed earliest, e.g., for Goal IV- or Goal IV Early, were prioritized ahead of measurments of equal priority needed later. Goal IV+ measurements are needed much later, so appear at the end of the priority list. Note that the investigations are ordered based on the highest priority measurements within each investigation, but the invertigations may also contain measurements at lower priority. The priority levels are the numbers 1-5 at the investigation level; the lettering at the investigation level is to separate investigations, but does not imply prioitiztion within each number level. For example: *Investigations #1A-1B contain the measurements judged to be of indistinguishable highest priority.*

Table IV-1 Partial listing of P-SAG Strategic Knowledge Gaps and Gap-filling Activities with priority and timing. This table focuses on the Gap-filling Activities (GFAs, equivalent to measurements) to be performed at Mars. From P-SAG (2102). See the full P-SAG report and associated matrix for details, including technology demonstrations and investigations not needing Mars flight opportunities, at http://mepag.jpl.nasa.gov/reports/.

SKG	Gap filling activity (GFA)	Priority	Timing
A1. Upper Atmosphere.	A1-1. Global temperature field.	High	IV-
	A1-2. Global aerosol profiles and properties	High	IV-
	A1-3. Global winds and wind profiles	Medium	IV-
A3. Orbital Particulates.	A3-1. Orbital particulate environment	Medium	IV-
B1. Lower Atmosphere.	B1-1. Dust Climatology	High	IV Late
	B1-2. Global surface pressure; local weather	High	IV Early
	B1-3. Surface winds	Medium	IV Early
	B1-4. EDL profiles	Medium	IV Early
	B1-5. Atmospheric Electricity conditions	Low	IV Late
B2. Back Contamination	B2-1. Biohazards	High	IV Early
B3. Crew Health & Performance	B3-1. Neutrons with directionality	Medium	IV Late
	B3-2. Simultaneous spectra of solar energetic particles in space and in the surface.	Medium	IV Late
	B3-4. Spectra of galactic cosmic rays on surface.	Medium	IV Late
	B3-5. Toxicity of dust to crew	Medium	IV Late
B4. Dust Effects on Surface Systems	B4-1. Electricity	Low	IV Late
	B4-2. Dust physical, chemical and electrical properties	High	IV Late
	B4-3. Regolith physical properties and structure	Medium	IV Late
B5. Forward Contamination	B5-1. Identify and map special regions	High	IV Late
B6. Atmospheric ISRU.	B6-1. Dust physical, chemical and electrical properties	High	IV Late
	B6-2. Dust column abundances	Low	IV Late
	B6-3. Trace gas abundances	Low	IV Late
B7. Landing Site and Hazards.	B7-1. Regolith physical properties and structure	Medium	IV Late
	B7-2. Landing site selection	Medium	IV Late
	B7-3. Trafficability	Low	IV Late
D1. Water Resources	D1-3. Hydrated mineral compositions	High	IV+
	D1-4. Hydrated mineral occurrences	High	IV+
	D1-5. Shallow water ice composition and properties	Medium	IV+
	D1-6. Shallow water ice occurrences	Medium	IV+

A. Objective: Obtain knowledge of Mars sufficient to design and implement a human mission with acceptable cost, risk and performance.

<u>1A. Investigation</u>: Determine the aspects of the atmospheric state that affect aerocapture, Entry Design and Landing (EDL) and launch from the surface of Mars. This includes the variability on diurnal, seasonal and inter-annual scales from ground to >80 km in both ambient and various dust storm conditions. The observations are to directly support engineering design and also to assist in numerical model validation, especially the confidence level of the tail of dispersions (>99%).

Atmospheric precursor data requested in investigation 1A would reduce the risk of loss of crew and loss of mission primarily by reducing the risk during EDL. This data would also reduce the risk during aerocapture and launch from Mars. The level of acceptable risk is much lower for manned missions than robotic landers and significant additional atmospheric measurements would be required to support the engineering design and modeling fidelity necessary to reduce the risk. Thus the investigation 1A observations would be mission enabling. The combination of mission enabling observations and a reduction in the risk of loss of crew yields a high priority for the investigation.

The measurements listed in investigation 1A are designed to fulfill the needs of the consulted EDL engineers; in particular, those working on design studies for human class (~40t) landing systems for Mars. The observations are designed to both directly support engineering studies and to validate atmospheric numerical models. The latter are essential to help characterize the potential dispersion of parameters. Existing recent observations fulfill some of the measurement requirements, but are currently insufficient to provide the necessary fidelity for the engineering modeling. The current orbital record is not yet long enough and fails to provide good local time coverage. The surface observations are both too short and only exist at four locations.

The global nature of the measurements (spatially and temporally) is driven by two factors. First, global coverage avoids having to limit site selection due to lack of observations. Local time coverage may allow access to sites otherwise deemed dangerous when conditions are safe. Secondly, it provides context for weather prediction during critical events. The temperatures (measurements “a” and “f”) would provide the density information necessary to determine entry trajectories, atmospheric heating, and deceleration rates. The aerosol information (measurement “b”) is primarily necessary to understand and model the performance of guidance systems (especially optical systems). Surface pressure (measurement “c”) directly controls the total atmospheric mass and thus the altitude of critical events during EDL. The dust activity climatology (measurement “d”) is primarily designed to understand the statistical frequency of events and their expected durations (to determine the necessary margins for waiting them out in orbit or on the surface). The winds (measurement “e”) are designed to allow pinpoint landing of surface systems.

<u>Assumptions:</u>

We have not reached agreement on the minimum number of atmospheric measurements described above, but it would be prudent to instrument all Mars atmospheric flight missions to extract required vehicle design and environment information. Our current understanding of the atmosphere comes primarily from orbital measurements, a small number of surface meteorology stations and a few entry profiles. Each landed mission to Mars has the potential to gather data that would significantly improve our models of the Martian atmosphere and its variability. It is thus desired that each opportunity be used to its fullest potential to gather atmospheric data. Reconstructing atmospheric dynamics from tracking data is useful but insufficient. Properly instrumenting entry vehicles would be required.

Priority	**GFA**	**Gap-Filling Activity needed measurements**
Highest	A1-1	a. Make long-term (> 5 Martian year) observations of the global atmospheric temperature field (both the climatology and the weather variability) at all local times from the surface to an altitude >80 km. The global coverage would need observations with a vertical resolution ≤ 5 km as well as observations with a horizontal resolution of ≤ 10 km (the horizontal and vertical resolutions do not need to be met by the same observation).
Highest	A1-2	b. Make global measurements of the vertical profile of aerosols (dust and water ice) at all local times between the surface and >60 km with a vertical resolution ≤ 5 km. These observations should include the optical properties, particle sizes and number densities.
Highest	B1-2	c. Monitor surface pressure in diverse locales over multiple Martian years to characterize the seasonal cycle, the diurnal cycle (including tidal phenomena) and to quantify the weather perturbations (especially due to dust storms). The selected locations are designed to validate global model extrapolations of surface pressure. The measurements would need to be continuous with a full diurnal sampling rate > 0.01 Hz and a precision of 10^{-2} Pa. Surface meteorological packages (including temperature, surface winds and relative humidity) and upward looking remote sounding instruments (high vertical resolution temperature and aerosol profiles below ~10 km) would be necessary to validate model boundary schemes.
High	B1-1	d. Globally monitor the dust and aerosol activity, especially large dust events, to create a long term dust activity climatology (> 10 Martian years).
High	A1-3 B1-3	e. Make long-term (> 5 Martian year) observations of global winds and wind direction with a precision ≤ 3 m/s at all local times from 15 km to an altitude > 60 km. The global coverage would need observations with a vertical resolution of ≤ 5 km and a horizontal resolution of ≤ 300 km. Simultaneous with the global wind observations, profile the near-surface winds (< 15 km) with a precision ≤ 2 m/s in representative regions (plains, up/down windo of topography, canyons). The boundary layer winds would need a vertical resolution of ≤ 1 km and a horizontal resolution of ≤ 100 m. The surface winds would be needed on an hourly basis throughout the diurnal cycle. During the daytime (when there is a strongly convective mixed layer), high frequency wind sampling would be necessary.
Medium	B1-4	f. Occasional temperature or density profiles with vertical resolutions < 1 km between the surface and 20 km are also necessary (see “Assumptions” below).

<u>1B. Investigation</u>: Determine if the Martian environments to be contacted by humans are free, to within acceptable risk standards, of biohazards that might have adverse effects on the crew that might be directly exposed while on Mars, and on other terrestrial species if uncontained Martian material would be returned to Earth. Note that determining that a landing site and associated operational scenario would be sufficiently safe is not the same as proving that life does not exist anywhere on Mars.

The measurements described in Investigation 1B would aid in reducing risks associated with back planetary protection to acceptable, as-yet undefined, standards as they pertain to: 1) the human flight crew, 2) the general public, and 3) terrestrial species in general. The risks in question relate to the return of uncontained Martian material, such as regolith and dust, that would certainly be on the outside of the ascent vehicle, within the cabin, or even within the astronauts' bodies when the crew leaves Mars. As shown by our experience with Apollo, when the crews open the seals to their landed systems to carry out EVA explorations, it is impossible to avoid getting dust on the outsides of the spacesuits as well as into the living quarter. For robotic sample return missions, a step called "breaking the chain of contact" is necessary to avoid these kinds of problems, but for a crewed mission, this prevention is currently not thought to be possible. Since it would not be possible to prevent human contact with the dust, it is necessary to determine in advance whether or not that dust is biologically hazardous. The action of returning the astronauts to Earth at the end of the mission, along with any associated uncontained Martian material, could pose a low but as-yet undefined risk to the Earth's ecosystem. For this reason, the impact of the data from this investigation on mission design has been rated high (mission enabling) and the impact of the data on risk reduction has also been rated high (public safety), for a combined priority rating of high.

Priority	GFA	Gap-Filling Activity needed measurements
Highest	B2-1	a. Determine if extant life is widely present in the Martian near-surface regolith, and if the air-borne dust is a mechanism for its transport. If life is present, assess whether it is a biohazard. For both assessments, a preliminary description of the required measurements is described in the MSR Draft Test Protocol (Rummel et al., 2002). This test protocol would need to be regularly updated in the future in response to instrumentation advances and a better understandings of Mars and of life itself.
High	B5-1	b. Determine the distribution of Martian special regions (see also Investigation IV-2B below), as these may be "oases" for Martian life. If there is a desire for a human mission to approach one of these potential oases, either the mission would need to be designed with special protections, or the potential hazard would need to be assessed in advance.

<u>Assumptions:</u>

- It is assumed that during the human mission to Mars, breaking the chain of contact with the Martian surface would be impossible. Thus, uncontained Martian material would travel back to the Earth's biosphere.
- Furthermore, it is assumed that if a surface mission has EVA activity, the astronauts would come into contact with uncontained Martian material in the form of dust that would enter their habitat.

- It would not be possible to prove the absence of life, even in a specific environmenetal niche, using in situ experiments alone—analysis of returned samples would be required.
- The samples needed to test for dust-borne biohazards could be collected from any site on Mars that is subjected to wind-blown dust.
- At any site where dust from the atmosphere is deposited on the surface, a regolith sample collected from the upper surface would be sufficient--it would not be necessary to filter dust from the atmosphere.

References

Rummel, J.D., Race, M.S., DeVincenzi, D.L., Schad, P.J., Stabekis, P.D., Viso, M., and Acevedo, S.E., editors. (2002) A Draft Test Protocol for Detecting Possible Biohazards in Martian Samples Returned to Earth [NASA=CP-20-02-211842], NASA Ames Research Center, Moffett Field, CA.

<u>2A. Investigation</u>: Characterize the particulates that could be transported to hardware and infrastructure through the air (including natural aeolian dust and other materials that could be raised from the Martian regolith by ground operations), and that could affect engineering performance and *in situ* lifetime. Analytic fidelity sufficient to establish credible engineering simulation labs and/or performance prediction/design codes on Earth would be required.

Mars is a dry, dusty place. Past experience with surface operations on the Moon illuminated that that it would be difficult, nearly impossible to prevent dust from getting into different parts of the landed system. On the Moon, there were three primary anthropogenic dust-raising mechanisms (ranked according to increased importance): astronaut walking, rover wheels spinning up dust, and landing and takeoff of spacecraft. On Mars, there are also winds, which are capable of raising and transporting dust.

We need to understand the potential impacts of dust on the surface system. There are at least three potential deleterious effects that would need to be understood: 1) effects of dust on seals, especially seals that would need to be opened and then reestablished, 2) effect of dust on the electrical properties the surfaces on which it would accumulate (for example, the effect of dust on circuit boards), and 3) the corrosive chemical effects of Martian dust on different kinds of materials. Note that for the purpose of this investigation, we distinguish between the direct effects of Martian dust on human beings (Investigation #3C below) and the effect of dust on the engineering system that would keep the humans on Mars alive and productive. Significant data about dust properties, dust accumulation rates, and effects on mechanical surface systems on Mars have been obtained from MER (Opportunity and Spirit) and Phoenix, thus the impact of additional measurements of these properties are now ranked lower than in previous versions of this document. However, additional measurements of these properties at other sites would help to understand the range of conditions expected and might still have an impact of mission design.

An important strategy for pursuing this investigation would be to collect enough data about the Martian dust to be able to create a large quantity of a Martian dust simulant that could be used in engineering laboratories on Earth. These data could be best be collected by analysis of a returned sample.

Priority	**GFA**	**Gap-Filling Activity needed measurements**
High	B4-2 B6-1	a. A complete analysis of regolith and surface aeolian fines (dust), consisting of shape and size distribution, density, shear strength, ice content and composition, mineralogy, electrical and thermal conductivity, triboelectric and photoemission properties, and chemistry (especially chemistry of relevance to predicting corrosion effects), of samples of regolith from a depth as large as might be affected by human surface operations.
Low	B4-2 B6-1	b. Repeat the above measurements at a second site in different geologic terrane. Note this is not seen as a mandatory investigation/measurement.
Low	B6-2	c. Determine the column abundance and size-frequency distribution, resolved at less than scale height, of dust particles in the martian atmosphere.

<u>2B. Investigation</u>: Determine the Martian environmental niches that would meet the definition (as it is maintained by COSPAR) of "Special Region.[1]" It is necessary to consider both naturally occurring special regions, and those that might be induced by the (human-related) missions envisioned. Evaluate the vulnerability of any special regions identified to terrestrial biological contamination, and the rates and scales of the Martian processes that would allow for the potential transport of viable terrestrial organisms to these special regions.

The measurements described in this investigation relate to characterizing "Special Regions" on the Martian surface, either extant or possibly induced by a human mission. One of the major mission objectives of the proposed human mission would be to determine if and how life arose naturally on Mars. Therefore, data that contributes to the understanding of the location of extant Special Regions where Martian life could exist would be considered of the highest priority (mission enabling). This mission objective could be compromised, however, by inducing a Special Region through the engineering aspects and biological inputs innate to a human mission. The extent of this potential compromise would require data from the measurements described in this Investigation.

Priority	GFA	Gap-Filling Activity needed measurements
High	B5-1	a. Map the distribution of naturally occurring surface special regions as defined by COSPAR[5]. One key investigation strategy is change detection.

[1] A Special Region is defined as "a region within which terrestrial organisms are likely to propagate, or a region which is interpreted to have a high potential for the existence of extant Martian life. As of 2010, no Special Regions had definitively been identified, however as of this writing, HiRISE has only covered 1% of the Martian surface. It is presumed that the policy of protecting special regions from terrestrial contamination would continue into the era of human exploration.

3A. Investigation: Determine the orbital particulate environment in high Mars orbit that may impact the delivery of cargo and crew to the Martian system.

There may be a dust ring between Phobos and Deimos located in and around the equatorial plane of Mars. Knowledge of the presence of these particulates and their size frequency distribution would help mission architecture planning and engineering designs for cargo and human missions to Mars orbit.

Priority	GFA	Gap-Filling Activity needed measurements
Medium	A3-1	a. Spatial variation in size-frequency distribution of Phobos/Deimos ejecta particles in Mars orbit

<u>3B. Investigation:</u> Characterize in detail the ionizing radiation environment at the Martian surface, distinguishing contributions from the energetic charged particles that penetrate the atmosphere, secondary neutrons produced in the atmosphere, and secondary charged particles and neutrons produced in the regolith.

Risks to astronauts from radiation in space have been characterized for decades. Outside the protection of Earth's magnetic field and atmosphere, the ever-present flux of Galactic Cosmic Rays (GCRs) poses a long-term cancer risk. The particle energies in GCRs are so powerful that using shielding mechanisms as a mitigation would be in most situations possible but impractical. Superimposed on the continual GCR background are Solar Energetic Particles (SEPs), generated episodically by a component of solar activity known as Coronal Mass Ejections (CMEs). SEPs are composed primarily of protons, generally lower in energy than GCRs, and possess much higher number fluxes. An individual SEP event could be fatal to a crewmember if a crewmember is caught unprotected. Given the energy distribution and fluxes of typical SEP events, the use of shielding to mitigate their impact would be feasible but shielded areas might be limited in size due to mass constraints. Hence, avoiding SEP exposures would primarily rely on gaining an understanding of space weather, with predictive and monitoring capabilities for CMEs and the SEPs that often accompany them. By having such knowledge, precautionary measures and appropriate actions could be taken.

The central issue with radiation exposure on Mars involves validating radiation transport codes and other tools designed to simulate and predict the biological relevancy of being exposed to radiation on Martian surface by taking into account all of the major variables. On Earth, the relatively thick Earth atmosphere combined with a sizeable, global magnetic field effectively shields humanity from the direct exposure to SEP events and substantially reduces GCR fluxes. Conversely, the martian atmosphere is geometrically thinner and of lower density than Earth's, and lacks adequate global, intrinsic magnetic field, thus posing a higher risk to radiation exposure.

As energetic particles dissipate energy into the Martian atmosphere and regolith, they would also produce a host of secondary particles. These include neutrons, which can be highly biologically effective and therefore contribute a significant share of the dose equivalent. Radiation dose would not only vary with solar activity and GCR levels, but also with topography and regolith composition. While GCR energies would cause the majority of these particles to pass through the atmosphere, many SEP events would most likely deposit the bulk of their energy towards the atmosphere with a significant production of biologically relevant secondaries. Of these, the efficiency for the production of secondary neutrons is currently uncertain. Thus, GCRs and SEPs are fairly distinct in terms of the physics of their interaction with the atmosphere. During future missions, SEP intensities would most likely be forecasted and detected from the vantage point of space or Earth. Models and tools must account for the details of SEP energy deposition into the atmosphere to assess the impact of these events on the surface of Mars. Hence, successful development of these tools would require simultaneous, accurate measurements of the radiation field both above the atmosphere and on the surface, such that the inputs and resulting outputs of the model system are fully constrained.

MSL is carrying the Radiation Assessment Detector (RAD), designed to assess radiation hazards from both neutrons and energetic charged particles on the surface of Mars. MSL will provide ground-truth measurements of the radiation environment on the surface of Mars, for both GCR and the SEP events, which it will observe over the course of the MSL mission (nominally 2 years). These measurements will be useful in providing necessary boundary conditions to constrain radiation exposure models primarily for GCRs, whose input flux, energy spectra, and variations are approximately uniform over much of the length of the solar system, but never measured on the Martian surface. MSL will also characterize the contribution to the surface radiation environment of the SEP events which it samples; however, due to the highly variable spectral, spatial, and temporal properties of SEPs, the properties of the radiation input at the top of the atmosphere will be far less understood. Thus measurements on MSL will likely satisfy the listed measurement goals a and b below for GCRs only. The impact of SEPs will not be fully characterized on MSL, either due to solar variability (few or no significant CMEs during the mission) or more importantly, a lack of an orbital reference to compare the measured inputs and outputs from the Martian atmosphere (measurement goal c).

Priority	**GFA**	**Gap-Filling Activity needed measurements**
Medium	B3-4	a. Identification of charged particles at the surface from hydrogen to iron and measure particle energies from 10 MeV/nuc to 400 MeV/nuc along with LET measurement during solar min.
Medium	B3-1	b. Measurement of neutrons with directionality. Energy range from $\leq$10 keV to $\geq$100 MeV.
Medium	B3-2	c. Simultaneous with surface measurements, a detector should be placed in orbit to measure energy spectra in Solar Energetic Particle events.

<u>3C. Investigation</u>: Determine the possible toxic effects of Martian dust on humans.

A discussion about the importance of the potential toxic effects of Martian surface materials is detailed in the NRC report, "Safe on Mars" (2002), by the Committee on Precursor Measurements Necessary to Support Human Operations on the Surface of Mars. They considered the presence and distribution of CrVI, commonly called "hexavalent cromium," especially important to understand because it is a strong human carcinogen. None of the past missions to Mars have carried instrumentation capable of measuring this species. Also discussed in the report are other potential cancer-causing compounds, many of which are still of concern due to lack of sufficient data. Potential chronic effects like lung injury in the form of silicosis must also be studied in greater detail, preferably with a returned sample. Collection of data related to the measurements listed above is considered of highest priority from a risk perspective because the risk of insufficient data connects directly to the probability of loss of crew. In terms of impact on design, it was of comparatively less importance given the fact that EVA systems, as well as dust mitigation protocols and design features, would already be significant, driven by other environmental challenges and forward and back contamination protocols.

Priority	GFA	Gap-Filling Activity needed measurements
Medium	B3-5	a. Assay for chemicals with known toxic effect on humans. Of particular importance are oxidizing species (e.g., CrVI) associated with dust-sized particles. Might require a sample returned to Earth as previous assays have not been conclusive enough to retire risk.
Medium	B3-5	b. Fully characterize soluble ion distributions, reactions that occur upon humidification and released volatiles from a surface sample and sample of regolith of similar depth might be affected by human surface operations. Previous robotic assays (Phoenix) have not been conclusive enough to significantly mitigate this risk.
Medium	B3-5	c. Analyze the shapes of Martian dust grains with a grain size distribution (1 to 500 microns) sufficient to assess their possible impact on human soft tissue (especially eyes and lungs).

<u>3D. Investigation</u>: Characterize the properties of the martian regolith sufficiently to design systems that will land, work properly, and survive on the martian surface. Analytic fidelity sufficient to establish credible engineering simulation labs and/or performance prediction/design codes on Earth would be required.

Landing and working on Mars means interacting with the Martian surface, which is mostly regolith. Therefore it is important to understand the properties of the Martian regolith in order to design and operate systems on Mars. The main interactions include landing, roving, and siting habitats and other facilities. In addition, it may be desirable to excavate regolith materials, both to establish foundations for facilities and to use the regolith as an in situ resource.

Landing on Mars with human scale systems will likely include rocket propulsion to slow the vehicle down for landing. Blast ejecta from descent engines could exceed bearing capacity of soils, as demonstrated on the Phoenix and MSL missions. This can lead to excavation of holes under the landers as well as the ejection of materials that potentially damage other systems at the landing site.

Both landing and the construction of habitats and other facilities will require a surface with sufficient bearing strength to handle the load placed on the surface. In addition, excavation to establish foundations or to provide protection from the surface environment by, for example, burying habitats beneath the regolith to provide protection from radiation, will require understanding subsurface structure of the regolith in order to design and operate systems capable of excavating and using the regolith materials.

The regolith is also a potential resource. In bulk form it could be used to cover habitats as radiation shielding. It could also be used has a source material for extraction of water or other useful materials.

Priority	GFA	Gap-Filling Activity needed measurements
Medium	B7-1	a. Regolith physical properties and structure, including surface bearing strength; presence of significant heterogeneities or subsurface features of layering; and an index of shear strength.
Medium	B4-3 B7-1	b. Regolith particle shape and size distribution, as well as Flow Rate Index test or other standard flow index measurement on the regolith materials.
Medium	B7-1	c. Gas permeability of the regolith in the range 1 to 300 Darcy with a factor of three accuracy.
Medium	B4-3 B7-1	d. Determine the chemistry and mineralogy of the regolith, including ice contents.

<u>3E. Investigation</u>: Assess landing site-related hazards, including those related both to safe landing and safe operations within the possible area to be accessed by possible elements of a human mission.

A successful human surface mission would need to land safely at a site of significant scientific interest, and in terrain that would allow the astronauts to move about the site as part of their exploration activity. We know from experience with site selection for past robotic landers/rovers that sites with some of the most interesting scientific attributes also tend to have more difficult and risky terrain. Correctly understanding the trade-off between landing site hazards and expected scientific return for a crewed mission would be fundamental to realizing the full potential of sending humans to Mars. Landing site-related hazards can be grouped into two categories: 1) Hazards related to landing safely, and 2) Hazards related to the various movements at the Martian surface needed to achieve a mission's objectives. Hazards in both areas would be capable of causing mission-ending failures. In the case of safe landing, we know from experience with prior Mars landers that the following four factors are particularly relevant: the size and concentration of surface rocks, terrain slopes, and the concentration of dust. The specific safety thresholds for these parameters would depend on the specific design of the mission (for example, ground clearance provided by landing legs), but we know from prior experience that these factors have to be considered carefully for all landed missions at Mars.

In order for landed human missions to achieve their objectives, movement across the Martian surface would be required. This might manifest itself in establishing and maintaining necessary surface infrastructure, or in accessing specific scientific targets. Thus, trafficability hazards need to be considered. In the case of MER, both Spirit and Opportunity became embedded in soft soil while driving. Opportunity was able to extricate itself and continue driving, but Spirit was not. Other trafficability hazards include rock fields and steep slopes. Although the operation of the MER rovers has significantly improved our general understanding of the issues related to trafficability on the Martian surface, an assessement would need to be made on a site-by-site basis given the range of mobile elements associated with a human mission.

Priority	GFA	Gap-Filling Activity needed measurements
Medium	B7-2	a. Imaging of selected potential landing sites to sufficient resolution to detect and characterize hazards to both landing and trafficability at the scale of the relevant landed systems.
Low	B7-3	b. Determine traction/cohesion in Martian regolith throughout planned landing sites; where possible, feed findings into surface asset design requirements.
Low	B7-3	c. Determine vertical variation of *in situ* regolith density within the upper 30 cm for rocky areas, on dust dunes, and in dust pockets to within 0.1 g cm^3.

4A. Investigation: Assess atmospheric electricity conditions that might affect Mars Take-off, Ascent, and Orbit-Insertion (MTAO) and human occupation.

Atmospheric electricity has posed a hazard to aircraft and space launch systems on Earth, and might pose similar danger on Mars. Among many notable incidents was the lightning strike that hit the Apollo 12 mission during the ascent phase, causing the flight computer in the spacecraft to reset. Far from a random event, the strike was likely triggered by the presence of the vehicle itself, combined with its electrically conducted exhaust plume that provided a low resistance path to the ground. Future explorers on Mars might face similar risks during MTAO after the completion of the mission – due to charge suspended in the atmosphere by local, regional or global dust activity. The amount of charge contained in these events, their spatial and temporal variations, and discharge mechanisms remain largely unknown. Surface measurements of electrodynamic phenomena within the atmosphere (i.e., below the ionosphere) could reveal whether or not charge buildup is sufficient for large scale discharges, such as those that affected Apollo 12.

Electrified dust and discharge processes might also represent a hazard during surface operations, which might effect everything from static-discharge sensitive equipment to communications. Unknown frictional charging interactions ("triboelectricity") between EVA suits, rovers, and habitats might also come into play. Understanding the ground and atmospheric conductivity, combined with the electrical properties of dust, would help to constrain the magnitude of these risks.

Priority	GFA	Gap-Filling Activity needed measurements
Low	B1-5 B4-1	a. Measure the magnitude and dynamics of any quasi-DC electric fields that may be present in the atmosphere as a result of dust transport or other processes, with a dynamic range of 5 V/m-80 kV/m, with a resolution ΔV=1V, over a bandwidth of DC-10 Hz (measurement rate = 20 Hz)
Low	B1-5 B4-1	b. Determine if higher frequency (AC) electric fields are present between the surface and the ionosphere, over a dynamic range of 10 uV/m – 10 V/m, over the frequency band 10 Hz-200 MHz. Power levels in this band should be measured at a minimum rate of 20 Hz and also include time domain sampling capability.
Low	B1-5 B4-1	c. Determine the electrical conductivity of the Martian atmosphere, covering a range of at least 10^{-15} to 10^{-10} S/m, at a resolution ΔS= 10% of the local ambient value.
Low	B4-1	d. Determine the electrical conductivity of the ground, measuring at least 10^{-13} S/m or more, at a resolution ΔS of 10% of the local ambient value
Low	B1-5 B4-1	e. Determine the charge on individual dust grains equal to a value of 10^{-17} C or greater, for grains with a radius between 1-100 μm
Low	B1-5	f. Combine the characterization of atmospheric electricity with surface meteorological and dust measurements to correlate electric forces and their causative meteorological source for more than 1 Martian year, both in dust devils and large dust storms

<u>4B. Investigation</u>: Understand trace gas abundances and their potential to interfere with atmospheric ISRU processing.

The resources to support a human stay at the Martian surface would be C, O, and H for both life support and ascent propellant (see DRA 5.0). Key trades include quantifying the mass, power, and risk associated with the equipment necessary to acquire and process these three commodities from Martian resources compared to the mass, power, and risk of simply delivering them from Earth. One of the outcomes of the DRA 5.0 analysis was that in the case of C and O, the chemical pathways and processing equipment required to obtain these commodities from the Martian CO_2 atmosphere were so well understood and mechanically simple that it became logical to plan to acquire them via ISRU. Carbon and Oxygen acquired via ISRU could be used to supply breathing oxygen for the crew.

However, we do not understand in sufficient detail the properties of atmospheric constituents near the surface to determine the adverse effects on ISRU atmospheric processing system life and performance within acceptable risk for human missions. Dust is a concern for all surface systems, as described in Investigation 2A. Trace gas abundances and their potential to interfere with atmospheric ISRU processing are not completely understood, so measurement of the trace gas composition of the martian atmosphere are desired. Since the Martian atmosphere is well-mixed, it is close enough to isochemical that only a single advance measurement would be needed. The SAM instrument on MSL has sufficient capability to make this measurement.

Priority	GFA	Gap-Filling Activity needed measurements
Low	B6-3	a. Measure the trace gas composition of the martian atmosphere with sufficient resolution and accuracy to detemine the potential effects on atmospheric ISRU.

<u>Assumptions:</u>
Perchlorate was considered as a possible oxidant for producing ascent fuel, but a) a more readily form of oxidant exists from the Martian atmosphere (O_2 extracted from CO_2) and b) there is no known method for clearly distinguishing perchlorate from orbit, thus no measurements of perchlorate are called for at this time.

<u>5. Investigation</u>: Characterize potential key resources to support In Situ Resource Utilization (ISRU) for eventual human missions.

The resources to support a human stay at the Martian surface would be C, O, and H for both life support and ascent propellant (see DRA 5.0). Key trades include quantifying the mass, power, and risk associated with the equipment necessary to acquire and process these commodities from Martian resources compared to the mass, power, and risk of simply delivering them from Earth.

In the case of hydrogen (or equivalently, water), ISRU has the potential to have a substantial impact on mission affordability (particularly as related to the amount of mass to be delivered to the surface) especially for long-stay missions. Information gathered from MGS, Mars Odyssey, MEx, MER, Phoenix, MRO and telescopic observations have shown that H resources exist on Mars in at least three settings: hydrated minerals in rocks and soils, in ground ice, and in the atmosphere. This information has been of potential interest for ISRU. Nevertheless, it is unknown whether any of the resource deposits and the demands placed on the mission's processing system to extract the deposits would be compatible with the engineering, risk, and financial constraints of a human mission to Mars.

At this time it is not known where on Mars potential human exploration might occur, whether at multiple sites or repeated visits to the same site. However, a key implication is that delivery of high-mass ISRU processing equipment to a single site on Mars would likely cause future missions to return to the same site. Returning to a single site might not be in line with overall science objectives and this must be taken into account.

As is true of all extractive natural resources, determining whether a resource deposit is "ore" or "waste" cannot be determined without knowledge of *both* the resource and processing system. ISRU power estimates depend on mineral composition because of varying heating needs when extracting water from each mineral type. Therefore, deciding whether or not H-ISRU should be part of a future human mission scenario would require characterizing the candidate resource deposits on Mars and technology development work on Earth. The answer to this question could be best arrived through two sequential phases: Reconnaissance-scale characterization sufficent to make prioritization decisions (Phase I) and a detailed site-specific characterization sufficient to plan for specific mission design (Phase II).

<u>Hydrated minerals</u>:
Numerous deposits of hydrated silicate and sulfate minerals have been identified on Mars from spectroscopic measurements [e.g., Bibring et al. 2005]. These deposits are attractive candidates for ISRU because 1) they exist on the surface, thus their spatial distributions are easy to constrain using remote methods, 2) they exist in a variety of locations across the globe, thus provide many choices for mission landing sites, and 3) the low water activity in these minerals would preclude planetary protection issues. Limitations on existing measurements include: 1) uncertainty of volume abundance within the upper meter of the surface, 2) best available spatial resolution (~20 m/pixel) might not be sufficient for ISRU processing design, and 3) mechanical properties of H-bearing materials are not sufficiently constrained.

Subsurface ice:

Accessible, extractable hydrogen is likely at most high-latitude sites in the form of subsurface ice [Boynton et al., 2002; Feldman et al. 2002; Mitrofanov et al. 2002]. In addition, theoretical models can predict subsurface ice in some mid-latitude regions, particularly on poleward facing slopes [Aharonson and Schorghofer, 2006]. Indeed, ice at northern latitudes as low as 42° has been detected in fresh craters using high resolution imaging and spectroscopy. Based on observed sublimation rates and the color of these deposits, the ice is thought to be nearly pure with <1% debris concentration [Byrne et al. 2009]. Pure subsurface ice and other ice-cemented soil were also detected by the Phoenix mission [Smith et al., 2009]. Subsurface ice deposits have ISRU potential, but are ranked lower than deposits of hydrated minerals because 1) low-latitude ice deposits are currently thought to exist only in glacial deposits that are associated with high elevations and difficult topography, and 2) mid-latitude deposits have substantial overburden that would make mining difficult (and in some cases are also in areas of difficult topography).

Additional reconnaissance would be required to evaluate the excavatibility, overburden, and mission power/volume needs associated with each of these H-resource types more confidently. In-situ measurements would be fundamental when confirming the resource abundance associated with excavatibility, depth, and power necessary for processing the H-resource(s) at the chosen landing site. Thus, the following proposed measurement specifications for the choosen landing site include both initial reconnaissance and follow-up in-situ measurements.

Priority	**GFA**	**Gap-Filling Activity needed measurements**
High	D1-3 D1-4	High spatial resolution maps (~2 m/pixel) of mineral composition and abundance. Verification of mineral volume abundance and physical properties within approximately the upper 3 meters of the surface. Mineral identification must also be verified. Measurement of the energy required to excavate/drill the H-bearing material. Measurement of the energy required to extract water from the H-bearing material.
Medium	D1-5 D1-6	High spatial resolution maps (~100 m/pixel) of subsurface ice depth and concentration within approximately the upper 3 meters of the surface. Verification of ice volume abundance and physical properties within approximately the upper 3 meters of the surface. Measurement of the energy required to excavate/drill the H-bearing material. Measurement of the energy required to extract water from the H-bearing material.

Note:

The 2m spatial resolution is based on the measurements for terrestrial mineral prospecting, which is achieved by using a combination of high-resolution (2.5 m/pixel) visible imagery, lower resolution multispectral imagery (15-90 m/pixel), and ore formation models. This spatial resolution could potentially be achieved on Mars by using existing sensors—combining the highest-resolution visible imagery (~50 cm/pixel) with the highest-resolution spectral data (~18 m/pixel) for specific areas or regions. When using this technique, one would need to assume similar surface textures/albedos between resolutions.

References

Aharonson, O., and Schorghofer, N., 2006, Subsurface ice on Mars with rough topography: Journal of Geophysical Research-Planets, v. 111, E11007, doi:10.1029/2005JE002636.

Bibring, J. P., Langevin, Y., Gendrin, A., Gondet, B., Poulet, F., Berthe, M., Soufflot, A., Arvidson, R., Mangold, N., Mustard, J., Drossart, P., and Team, O., 2005, Mars surface diversity as revealed by the OMEGA/Mars Express observations: Science, v. 307, p. 1576-1581.

Boynton, W. V., Feldman, W. C., Squyres, S. W., Prettyman, T. H., Bruckner, J., Evans, L. G., Reedy, R. C., Starr, R., Arnold, J. R., Drake, D. M., Englert, P. A. J., Metzger, A. E., Mitrofanov, I., Trombka, J. I., d'Uston, C., Wanke, H., Gasnault, O., Hamara, D. K., Janes, D. M., Marcialis, R. L., Maurice, S., Mikheeva, I., Taylor, G. J., Tokar, R., and Shinohara, C., 2002, Distribution of hydrogen in the near surface of Mars: Evidence for subsurface ice deposits: Science, v. 297, p. 81-85.

Byrne, S., Dundas, C. M., Kennedy, M. R., Mellon, M. T., McEwen, A. S., Cull, S. C., Daubar, I. J., Shean, D. E., Seelos, K. D., Murchie, S. L., Cantor, B. A., Arvidson, R. E., Edgett, K. S., Reufer, A., Thomas, N., Harrison, T. N., Posiolova, L. V., and Seelos, F. P., 2009, Distribution of Mid-Latitude Ground Ice on Mars from New Impact Craters: Science, v. 325, p. 1674-1676.

Feldman, W. C., Boynton, W. V., Tokar, R. L., Prettyman, T. H., Gasnault, O., Squyres, S. W., Elphic, R. C., Lawrence, D. J., Lawson, S. L., Maurice, S., McKinney, G. W., Moore, K. R., and Reedy, R. C., 2002, Global distribution of neutrons from Mars: Results from Mars Odyssey: Science, v. 297, p. 75-78.

Mitrofanov, I., Anfimov, D., Kozyrev, A., Litvak, M., Sanin, A., Tret'yakov, V., Krylov, A., Shvetsov, V., Boynton, W., Shinohara, C., Hamara, D., and Saunders, R. S., 2002, Maps of subsurface hydrogen from the high energy neutron detector, Mars Odyssey: Science, v. 297, p. 78-81.

Smith, P. H., Tamppari, L. K., Arvidson, R. E., Bass, D., Blaney, D., Boynton, W. V., Carswell, A., Catling, D. C., Clark, B. C., Duck, T., DeJong, E., Fisher, D., Goetz, W., Gunnlaugsson, H. P., Hecht, M. H., Hipkin, V., Hoffman, J., Hviid, S. F., Keller, H. U., Kounaves, S. P., Lange, C. F., Lemmon, M. T., Madsen, M. B., Markiewicz, W. J., Marshall, J., Mckay, C. P., Mellon, M. T., Ming, D. W., Morris, R. V., Pike, W. T., Renno, N., Staufer, U., Stoker, C., Taylor, P., Whiteway, J. A., and Zent, A. P., 2009, H2O at the Phoenix Landing Site: Science, v. 325, p. 58-61.